# High Aspect Ratio Electron Beam, High Efficiency Interaction Structure, and High Power Amplifier Design*

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DARPA/MTO High frequency Integrated Vacuum Electronics (HiFIVE) Program

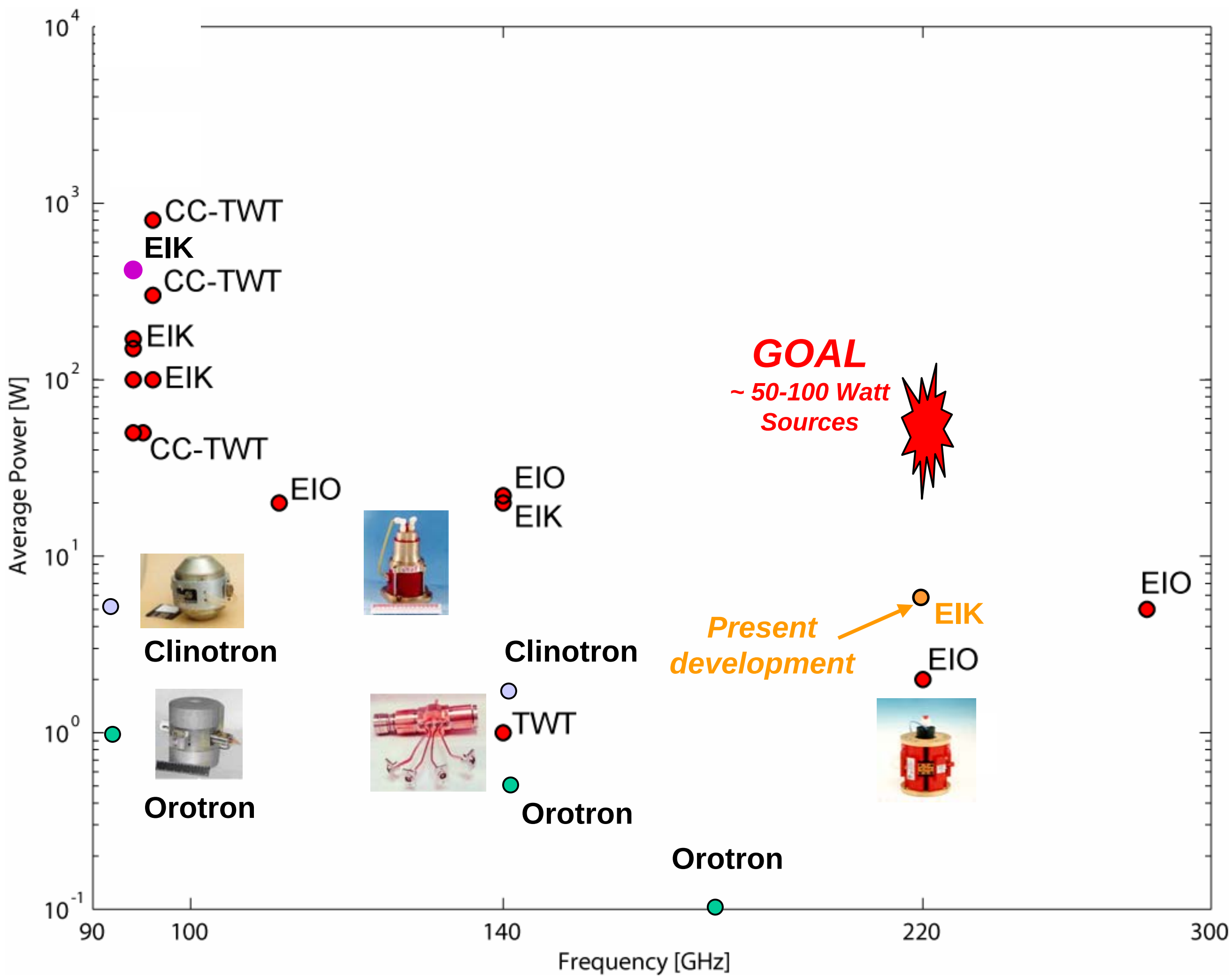
* Work sponsored by DARPA/MTO

# High Aspect Ratio Electron Beam

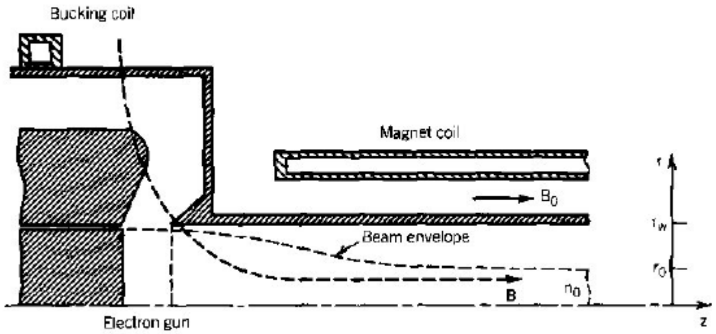
and

# High Efficiency Interaction Structure

# Upper MM-Wave Slow Wave Sources State-of-the-Art



# Magnetic Focusing and Transport of Electron Beams – a Key Limiting Factor




From S. Humphries, "Charged Particle Beams"

- **Beam envelope equation:**

$$R'' + k^2 R - \frac{K}{R} - \frac{\varepsilon^2}{R^3} = 0$$

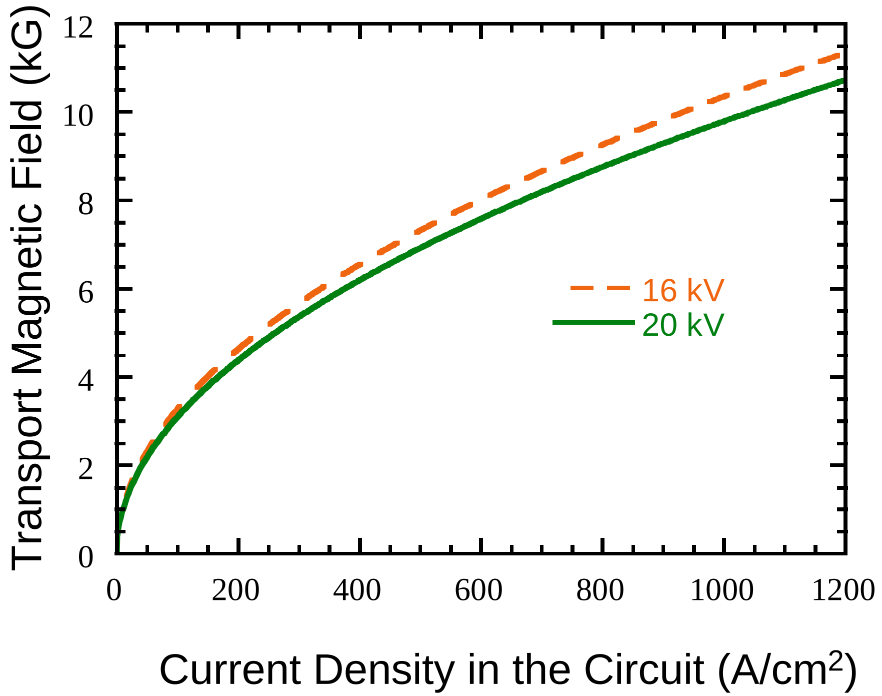
- **Brillouin flow:**

$$k^2 R - \frac{K}{R} = 0 \Rightarrow B_{Brillouin} = 262\left(\frac{J^{1/2}}{V_b^{1/4}}\right) \text{Gauss}$$

$$K \equiv \frac{2I}{(\beta\gamma)^3 (17.0kA)}$$

- ***J*** **in A/cm²**
- **$V_b$ in kV**

$$B_{transport} \sim 2.5 \times B_{Brillouin}$$



# Power vs. Frequency ( $f$ ) Scaling for Round Beam Devices – Basic Issues

Fixed Upper Limit on Circuit Magnetic Field $B_{max}$ due to Permanent Magnet Technology (~ 11 kG)

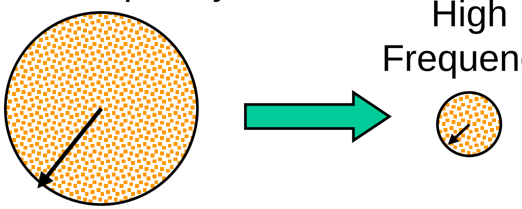
Practical Upper Limit on Beam Voltage Due to Systems Limitations (~ 20 kV)

→ Fixed Upper Limit on Current Density in the Circuit $J_{max}$ (~1200 A/cm$^2$)

Low Frequency

High Frequency

*Beam cross section*



| | |
|---|---|
| Circuit Radius | $\sim 1/f$ |
| Beam Radius | $\sim 1/f$ |
| Beam Area | $\sim 1/f^2$ |
| Beam Current ( $I_b$ ) | $\sim J_{max}(1/f^2)$ |

**Several Possible Scalings. For Example…..**

Circuit not breakdown limited (fixed beam voltage $V_b$)

Beam Power ( $P_b$ ) $\sim V_b I_b \sim V_c J_{max} (1/f^{2})$

Output Power $\sim \eta P_b \sim (1/f^{0.5})(1/f^{2}) \sim (1/f^{5/2})$

Circuit breakdown limited (beam voltage $V_b$ scaling as $1/f$ )

Beam Power ( $P_b$ ) $\sim V_b I_b \sim J_{max} (1/f^{3})$

Output Power $\sim \eta P_b \sim (1/f^{0.5})(1/f^{3}) \sim (1/f^{7/2})$

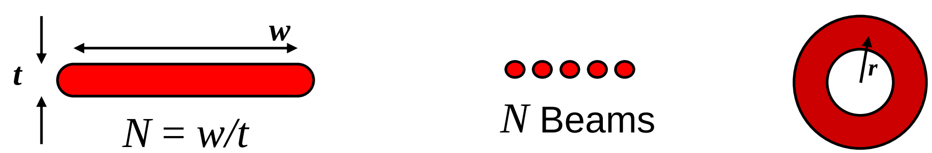
Interaction impedance limited

Output Power $\sim \eta R I_b^{2} \sim (1/f^{0.5})(1/f^{4}) \sim (1/f^{9/2})$

# Scaling formulae for traveling wave devices and standing wave devices

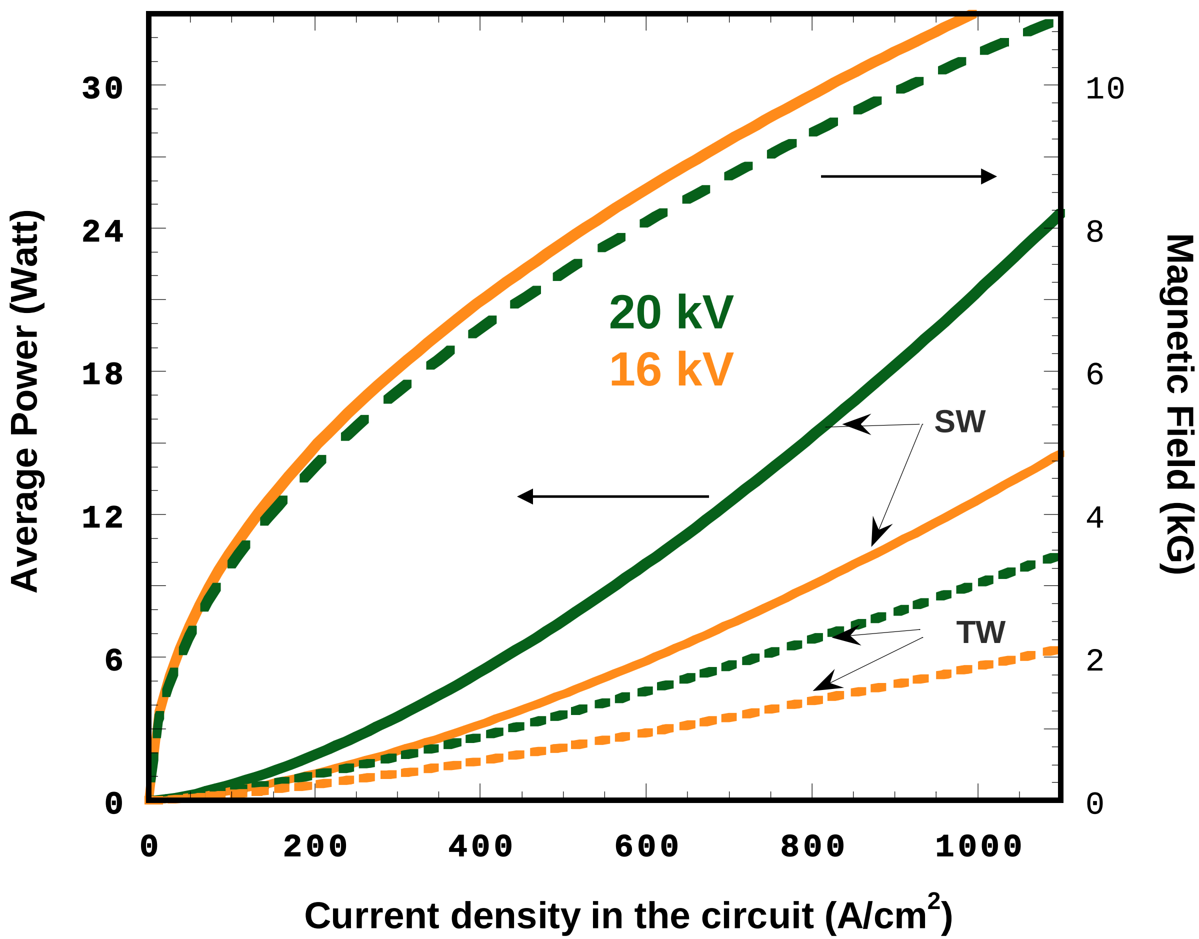
| Device | Traveling wave | Standing wave |
|---|---|---|
| **Peak RF Power (W)** | $N \times 24\left(\frac{1}{f}\right)^{8/3}(V_b)^{13/6}(J)^{4/3}$ | $N \times 150\left(\frac{1}{f}\right)^{13/4}(V_b)^{5/2}(J)^{3/2}$ |
| **Peak Elect. Eff. (%)** | $14.4\left(\frac{1}{f}\right)^{2/3}(V_b)^{1/6}(J)^{1/3}$ | $48\left(\frac{1}{f}\right)^{5/4}(V_b)^{1/2}(J)^{1/2}$ |
| **CW RF Power (W)** | $N \times 2.4\left(\frac{1}{f}\right)^{8/3}(V_b)^{13/6}(J)^{4/3}$ | $N \times 15\left(\frac{1}{f}\right)^{13/4}(V_b)^{5/2}(J)^{3/2}$ |

Numeric values from state-of-the art anchor points, $f$ in GHz, $V_b$ in kV, and $J$ in A/cm$^2$. $N$ is the beam aspect ratio or number of beams.

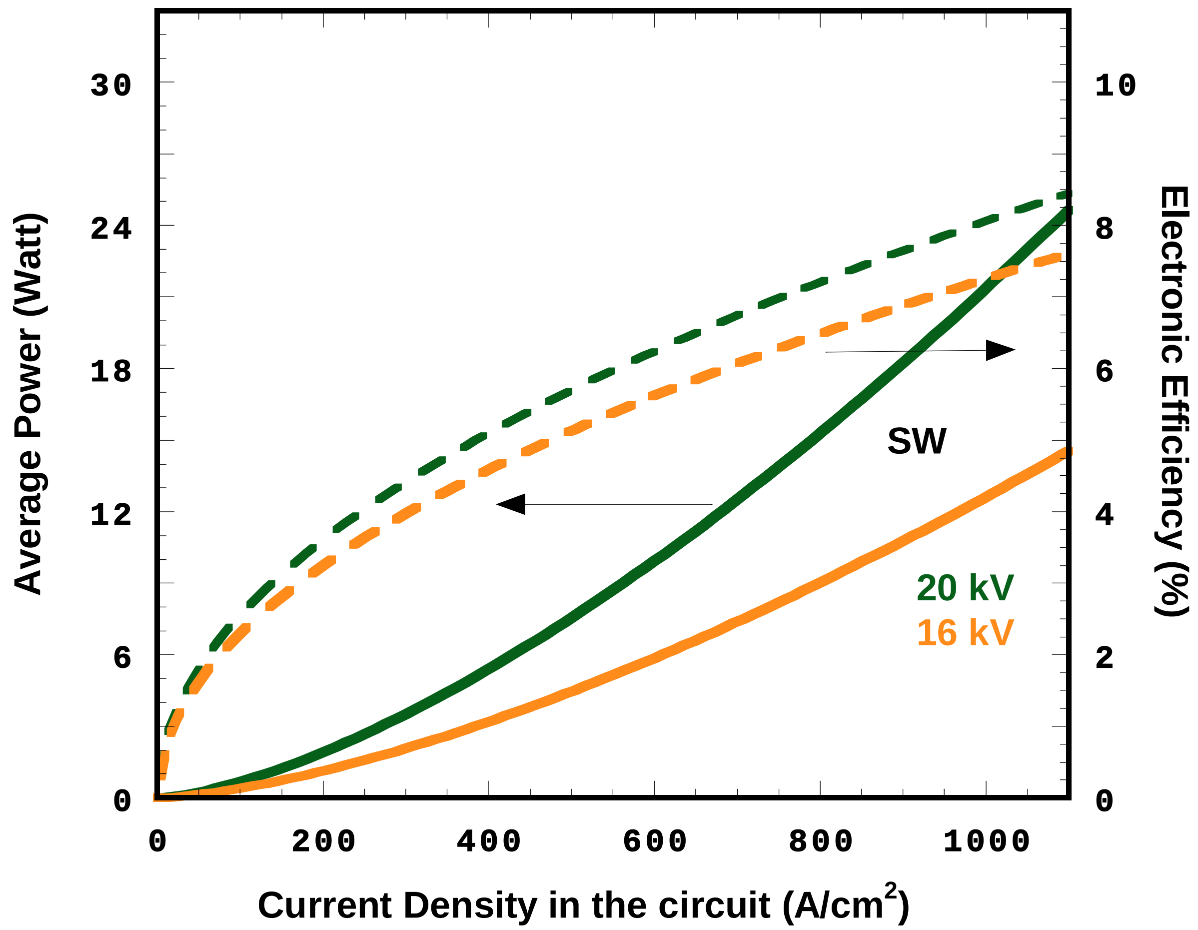



$N = w/t$ | $N$ Beams | $N = 2\pi r/t$

# Scaling at 220 GHz



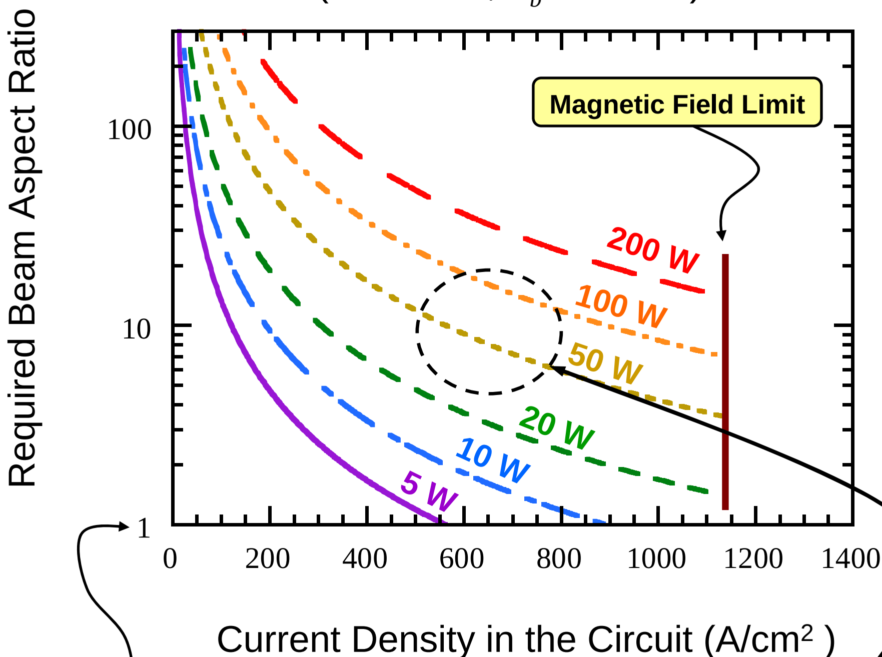
# More Scaling at 220 GHz



# Projected 220 GHz Performance at V = 16 kV

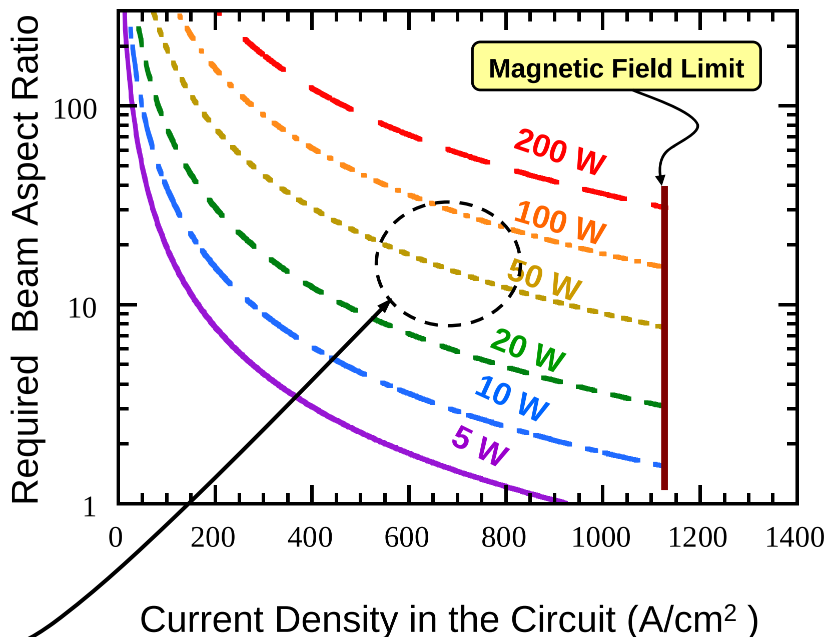
## SW

Curves for Various CW Output Powers
( 220 GHz, $V_b$ = 16 kV )




## TW

Curves for Various CW Output Powers
( 220 GHz, $V_b$ = 16 kV )



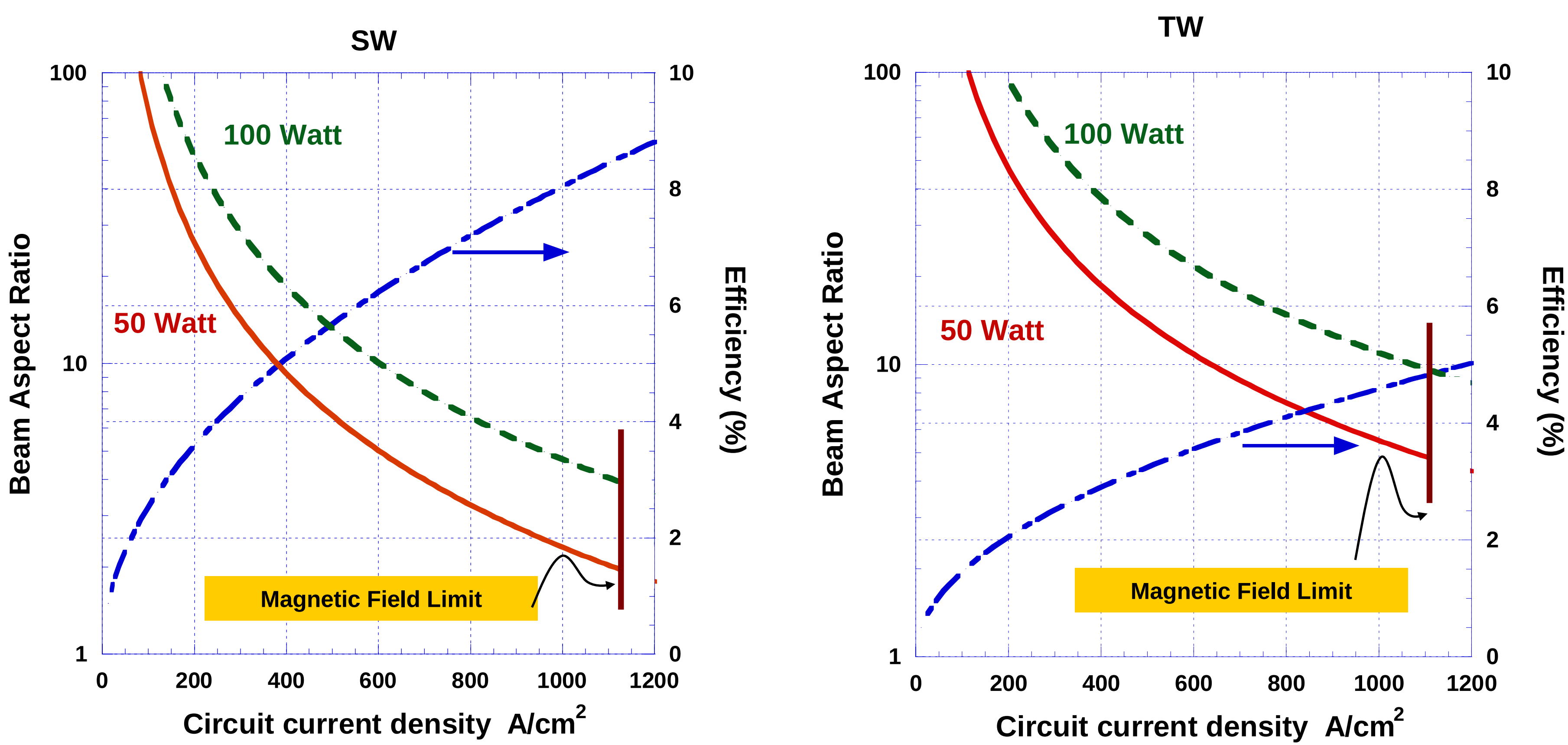

**Round Beam**
**(Aspect Ratio = 1 )**

Current density ~ 750 A/cm$^2$

Beam aspect ratio ~ 10-25

50 W Output Power at 220 GHz

# Projected 220 GHz Performance at V = 20 kV

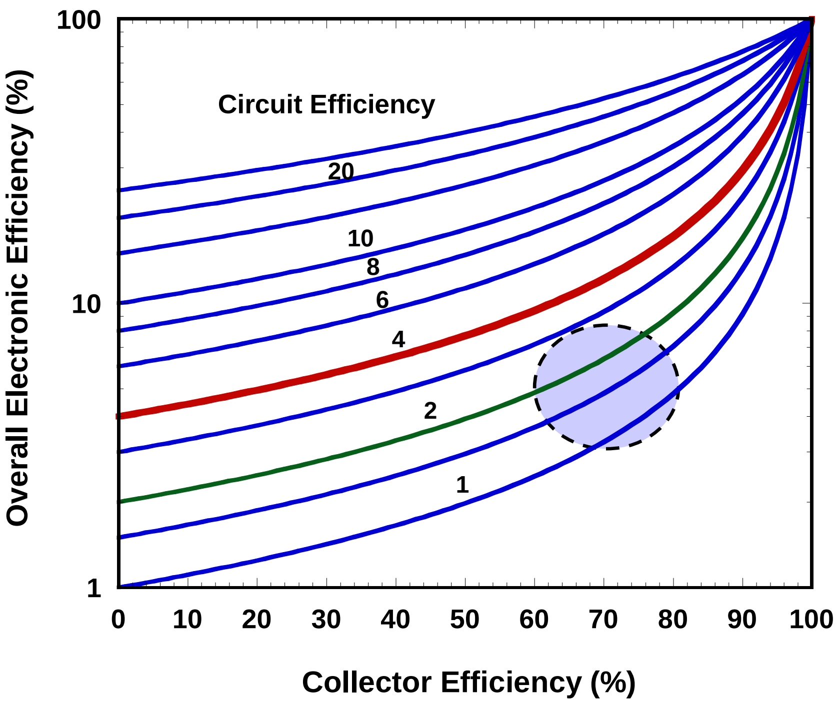


# Multi-stage Depressed-Collector Technology for Efficiency Enhancement

## Electronic Efficiency

$$\eta_{total} \approx \frac{\eta_{circuit}}{1-\eta_{collector}(1-\eta_{circuit})}$$

Multi-stage depressed collector
State-of-the-art efficiency > 80%.

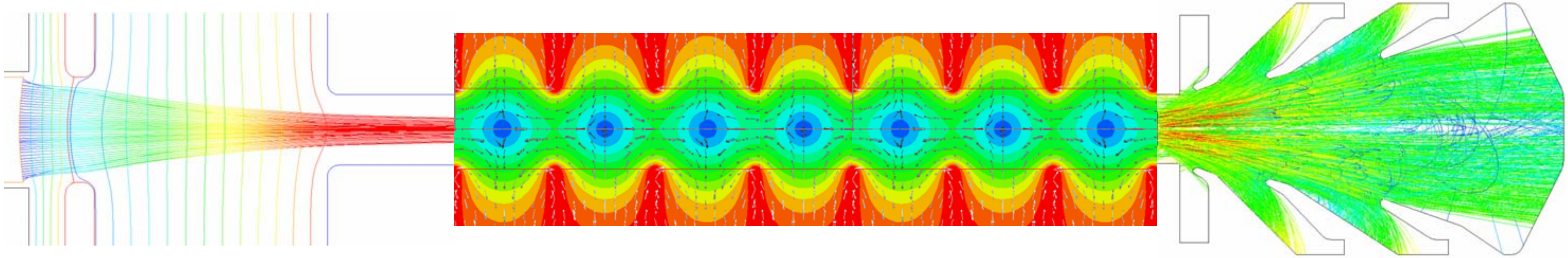


# Component Design

- MICHELLE 3D and Maxwell 3D addressing the beam generation, propagation and collection

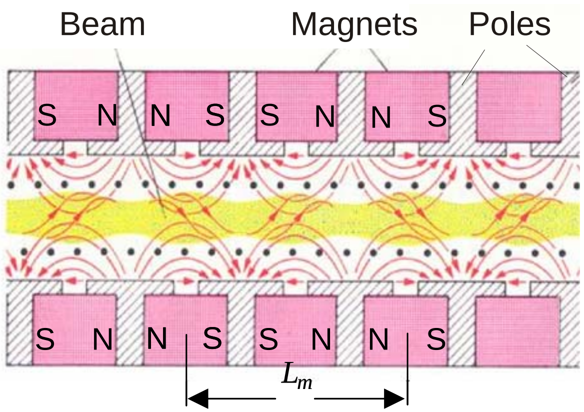
Beam formation | Beam transport | Beam energy recovery

**Cathode** **Anode** **PCM magnetic field** **Multi-stage depressed collector**



# Focusing Options with Permanent Magnets

- **Periodic Cusp Magnet (PCM) fields**
  - Very common focusing scheme for conventional tubes
  - Challenges
    - Obtaining sufficient field
    - Transverse plane focusing
    - Small parts
    - Magnetization homogeneity
  - Advantages
    - Stable transport for long distances




$$2\omega_p^2 \le \left(\frac{eB_0}{m}\right)^2 << 16\frac{e}{m}V\left(\frac{\pi}{L_M}\right)^2$$

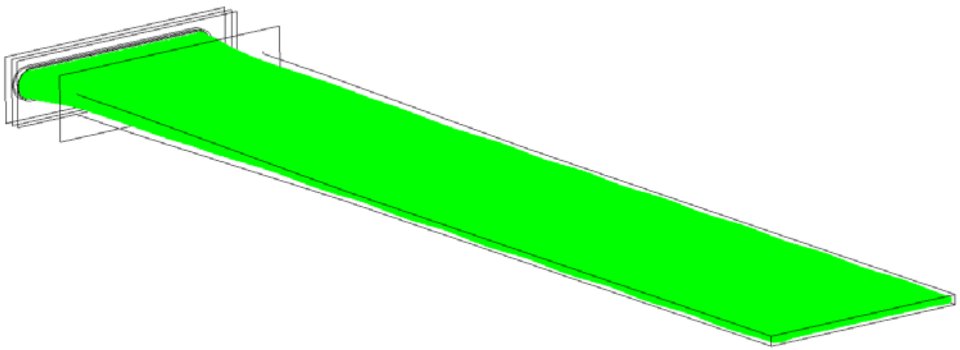
- **Permanent Magnet (PM) axial (solenoidal) fields**
  - Used in some compact MMW tubes
  - Challenges
    - Diocotron instability
  - Advantages
    - Higher fields obtainable
    - Simple magnetic geometry

$$B[kG] > 0.32\frac{I\,[A]}{V\,[kV]}\frac{L\,[cm]}{A_{beam}\,[cm^2]}$$

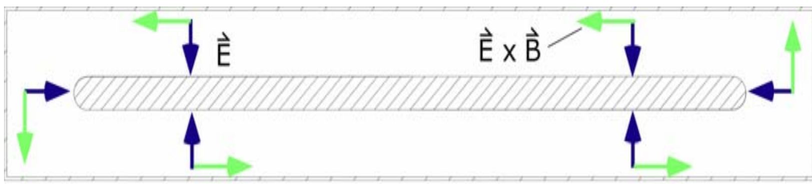
*Condition for $L < L_{Diocotron}$*

# Sheet-Beam Transport in Solenoidal Field

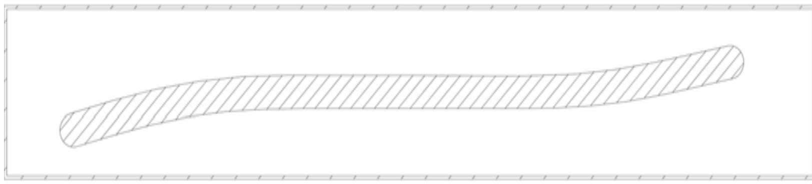
**MICHELLE Simulation**



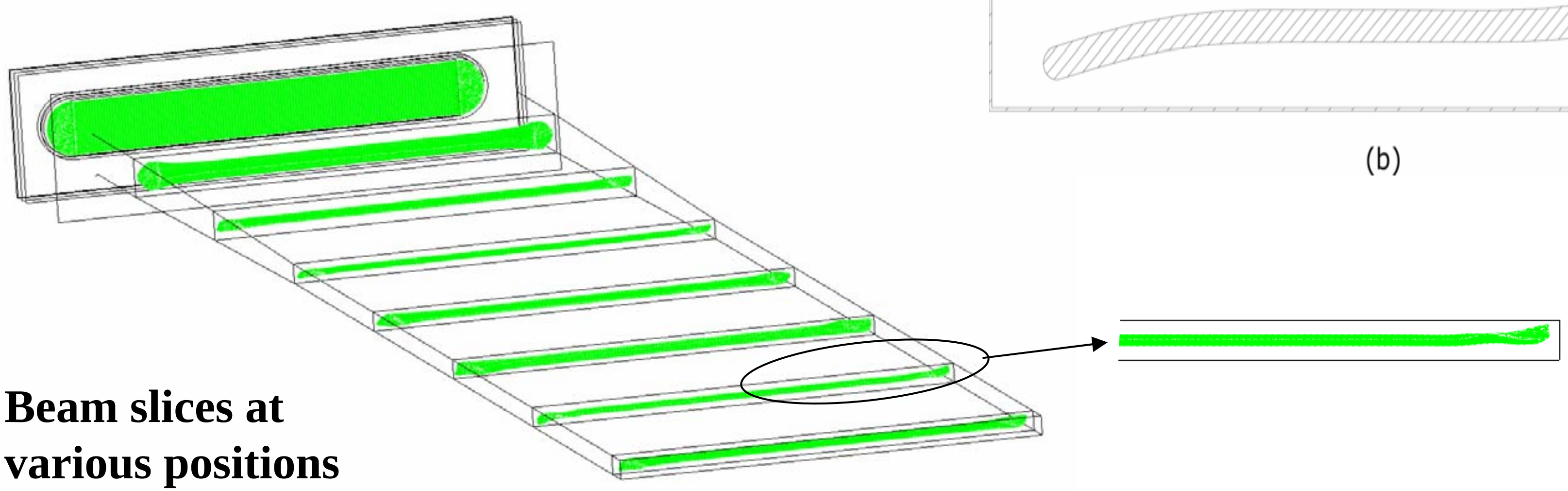
***ExB Drift***
***Diocotron Instability***




(a)



(b)

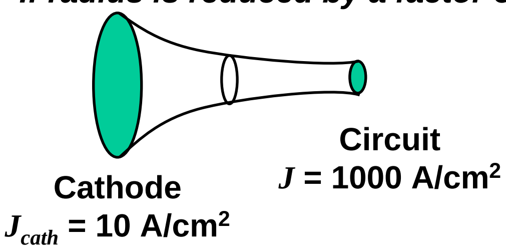


**Beam slices at various positions**

# Beam Compression Requirements

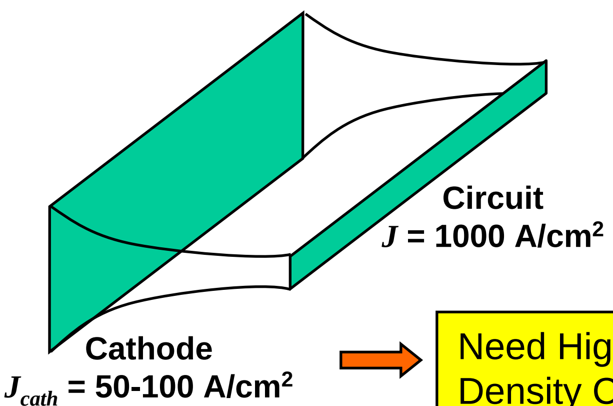
**Round Beam – Compression is Two Dimensional**

***If radius is reduced by a factor of 10***

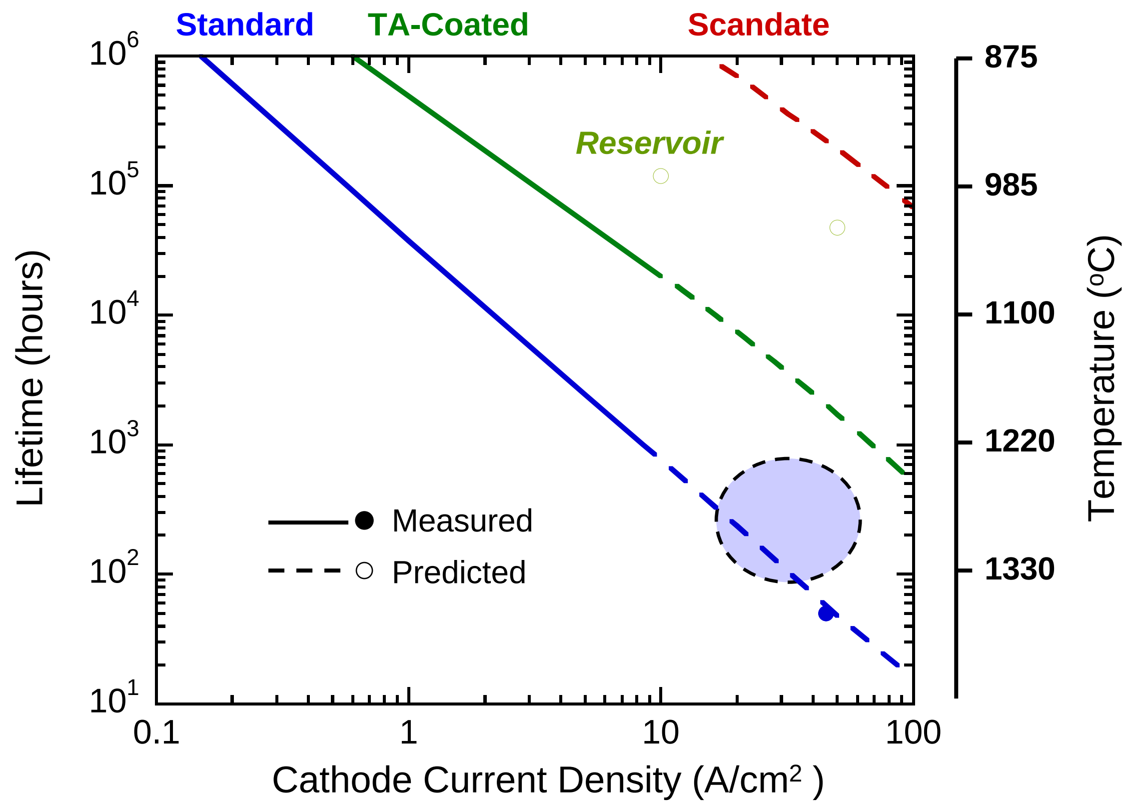



**Sheet Beam – Compression is Mainly One Dimensional**

***If height is reduced by a factor of 10-20***




Need High Current Density Cathodes!!



# High Power Amplifier Design

# High Power Amplifier Design

- Perform theoretical analyses and simulations using physics-based modeling and simulation tools, such as *MICHELLE, CHRISTINE and TESLA (NRL)* and COTS software, such as:

  *MAXWELL and HFSS (http://www.ansoft.com/),*

  *MAGIC (http://www.magictoolsuite.com/),*

  *ANALYST (http://www.staarinc.com/),*

  *ANSYS (http://www.ansys.com/)*

  – Analyze beam-wave interaction in circuit

  > Power > Efficiency > Bandwidth

  – Determine limitations and devise solutions to key problems

  > Stability > Breakdown > Thermal

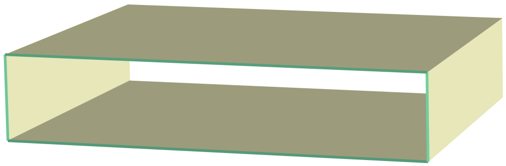
- Design, fabricate, and cold test most promising structures to determine optimum configuration and fabrication techniques

# Higher Order Modes in Sheet Beam Devices

- Sheet beam RF structures are inherently overmoded
  - Beam/circuit lateral size becomes large compared to RF wavelength
  - Many competing modes appear with similar resonant frequencies
- Need an understanding of mode competition

**Mode competition is a universal problem for sheet beam RF amplifiers**

Consider a simple waveguide:


a

b

TM mode cutoff frequencies are:

$$\frac{\omega_{m,n}^2}{c^2} = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2$$

m = 1,2,3… n = 1,2,3…

When a ≈ b $\omega_{1,1} << \omega_{1,2}$

(Distinct fundamental mode)

When a << b $\omega_{1,1} \approx \omega_{1,2} \approx \omega_{1,3} \approx \cdots$

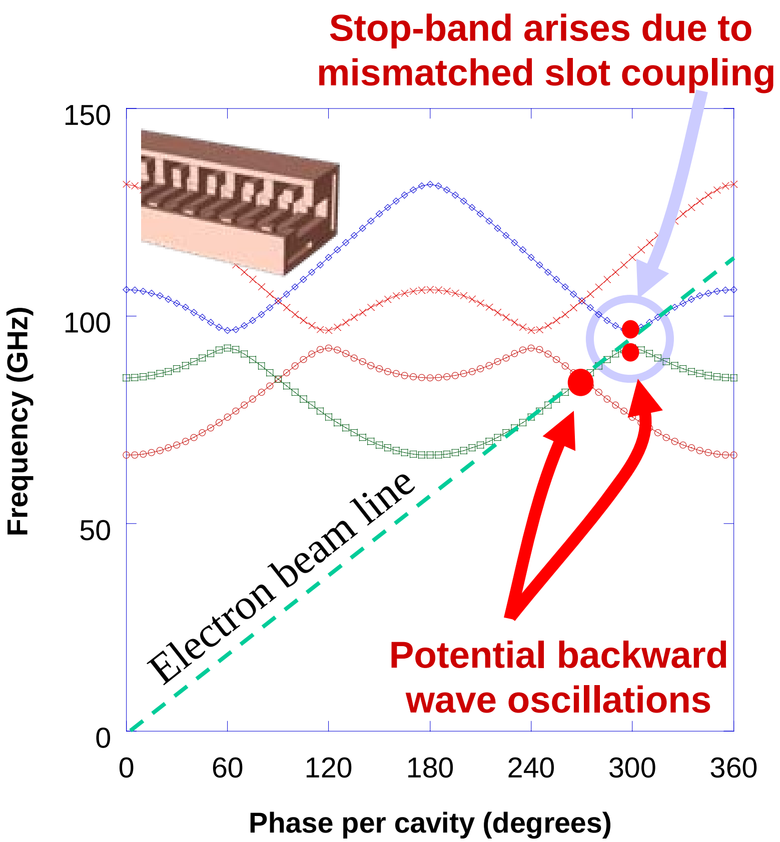
(Many modes are almost degenerate)

Modes have different transverse structure:

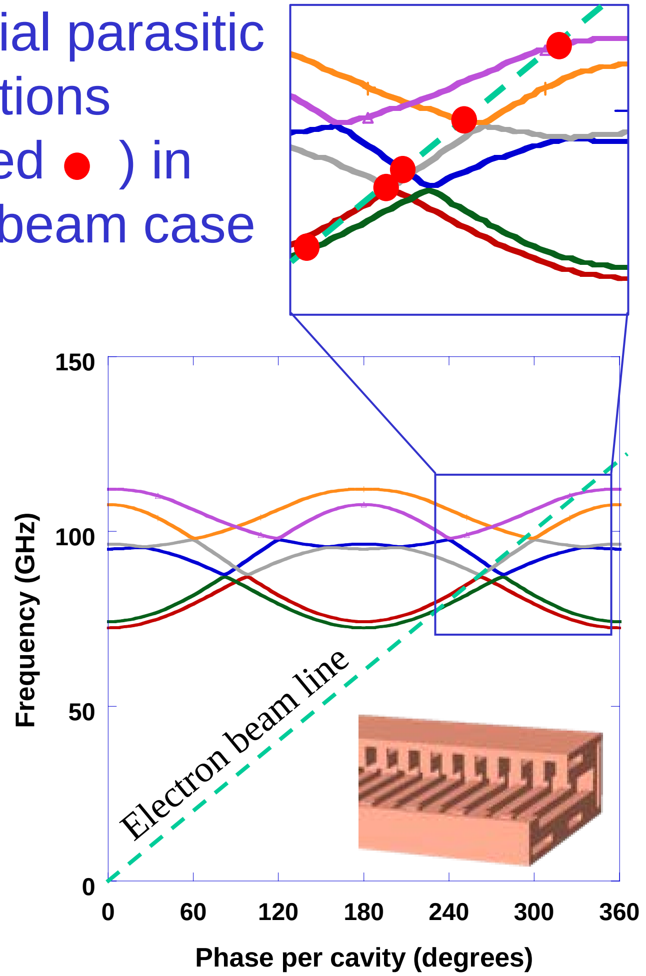
$$E_z \propto \sin\frac{\pi x}{b},\ \sin\frac{2\pi x}{b},\ \sin\frac{3\pi x}{b},\cdots$$

# Sources of Mode Competition

- Competing interactions:
  - Backward wave oscillation (BWO)
  - Stop-band oscillations
  - Both TM and TE modes interact

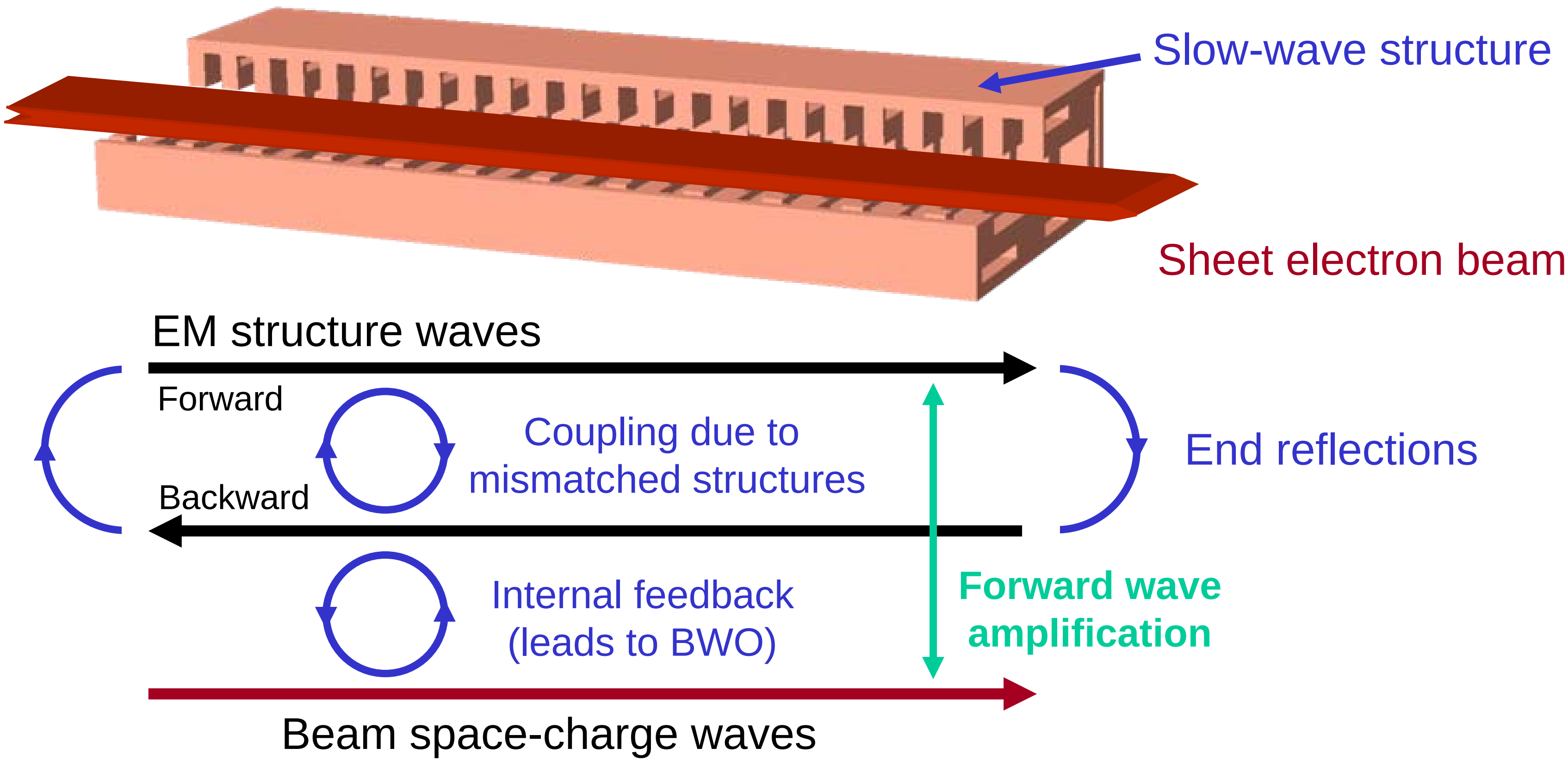



Dense spectrum of potential parasitic oscillations (marked ● ) in sheet beam case



# Physical Processes Affecting Stability

## Many processes provide feedback, potentially causing oscillation




- BWO oscillation occurs when the gain region exceeds a threshold length
- Stop-bands can significantly decrease this critical length